Soft particle production and energy flow at the LHC

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Hadron Collider Physics Symposium 2012

Introduction

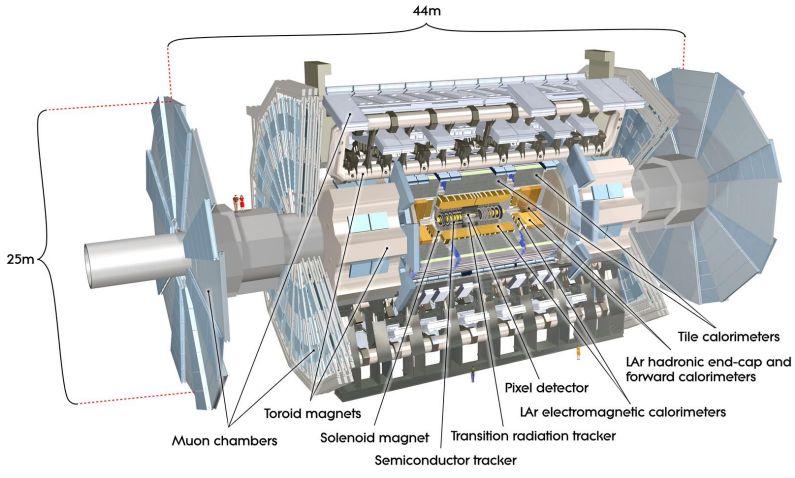
Presenting measurements from ATLAS and CMS of a variety of quantities sensitive to soft-QCD processes

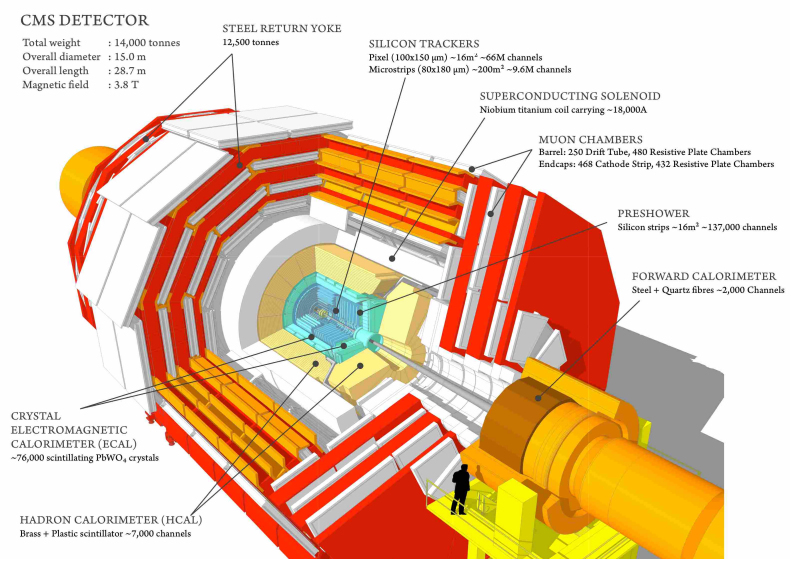
New, precision measurements that challenge theoretical predictions

Useful for MC tuning: there are many areas where existing models do not describe the data

Provides a comparison to LHC Pb-Pb results

ATLAS and CMS





Using the innermost tracking systems of the two detectors, and the calorimeters in the case of jet measurements

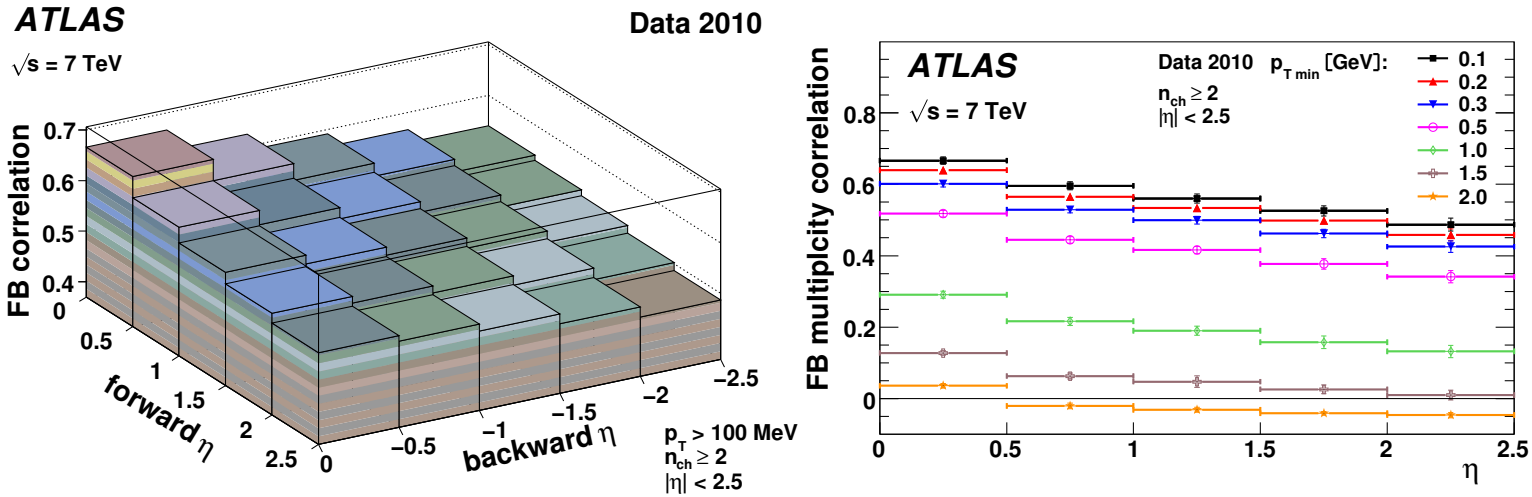
Forward-Backward correlations

Divide the detector into the 'forward' (positive η and z) and 'backward' (negative) regions
Define the forward-backward multiplicity correlation:

$$\rho_{fb}^{n} = \frac{\langle (n_f - \langle n_f \rangle)(n_b - \langle n_b \rangle) \rangle}{\sqrt{\langle (n_f - \langle n_f \rangle)^2 \rangle \langle (n_b - \langle n_b \rangle)^2 \rangle}}$$
$$= \frac{\sum x_f x_b}{N \sigma_f \sigma_b}$$

Can also define the correlation for $\sum p_{\mathrm{T}}$ in place of n

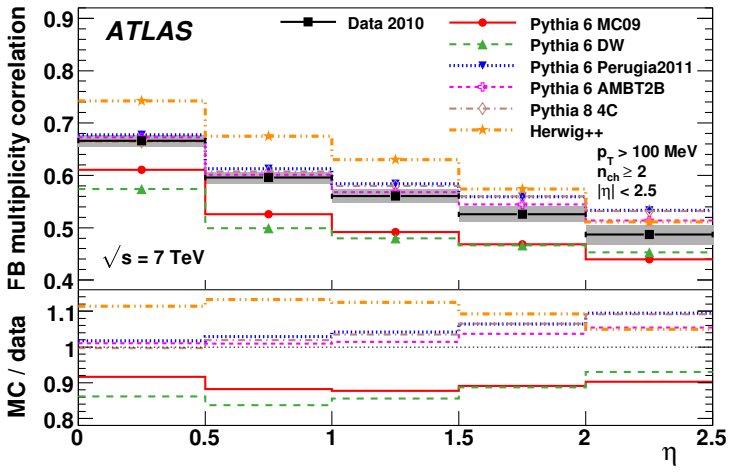
Forward-Backward correlations

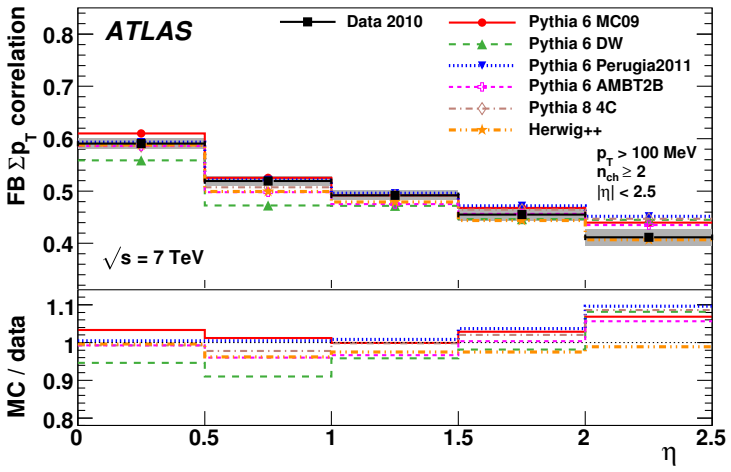


The correlation varies with $\Delta\eta$, rather than the particular η regions in question

Comparing symmetric regions in subsequent results

Forward-Backward correlations



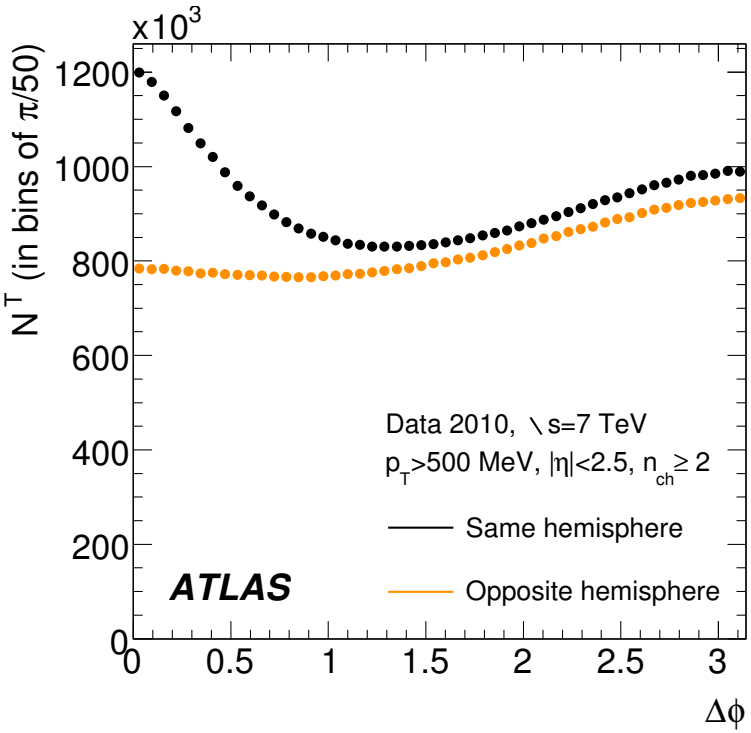


There are similar trends for the multiplicity and $\sum p_{\mathrm{T}}$ correlations, but the multiplicity is not as well described by MC

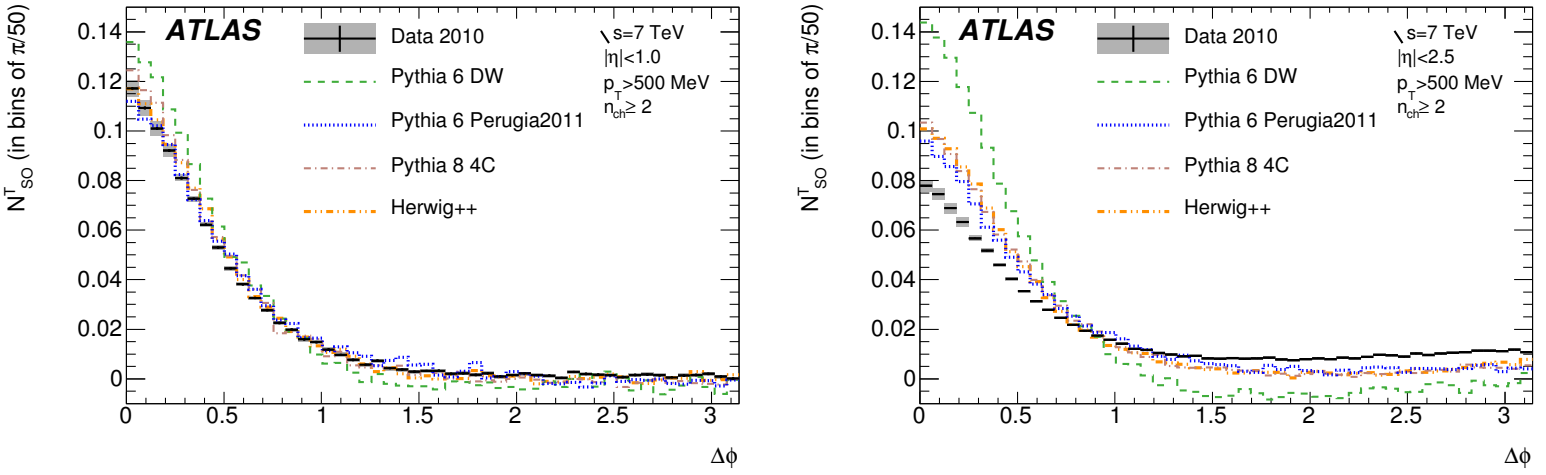
Azimuthal correlation variable

For the number of selected charged particles N^T, compare the $\Delta\phi$ distributions in the same and opposite-sign η regions to the highest p_{T} particle:

$$N^T_{SO} = \frac{N^T_{same} - N^T_{opp}}{\sum N^T_{same} - N^T_{opp}}$$



Azimuthal correlation



As the $|\eta|$ range increases, so the MC models diverge from the data

Note the range of variation in data is much larger than MC

Azimuthal ordering

Can also investigate the azimuthal ordering of charged hadrons

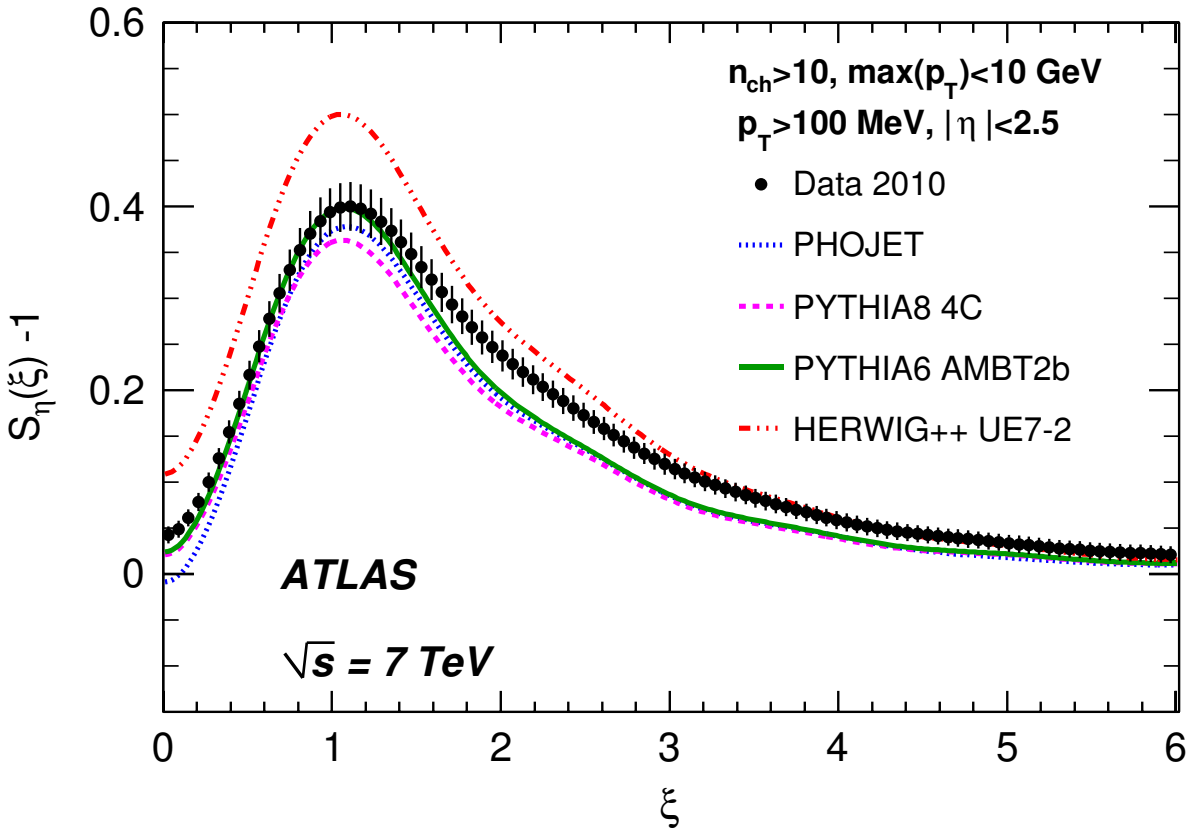
The opening angle between two direct hadrons measures the helical phase difference between corresponding points on a (Lund) string

Examine this variable:

$$S_\eta(\xi) - 1 = \frac{1}{N_{\text{events}}} \sum_{\text{events}} \frac{1}{n_{\text{ch}}} \sum_{i \neq j} \cos(\xi \Delta\eta_{ij} - \Delta\phi_{ij})$$

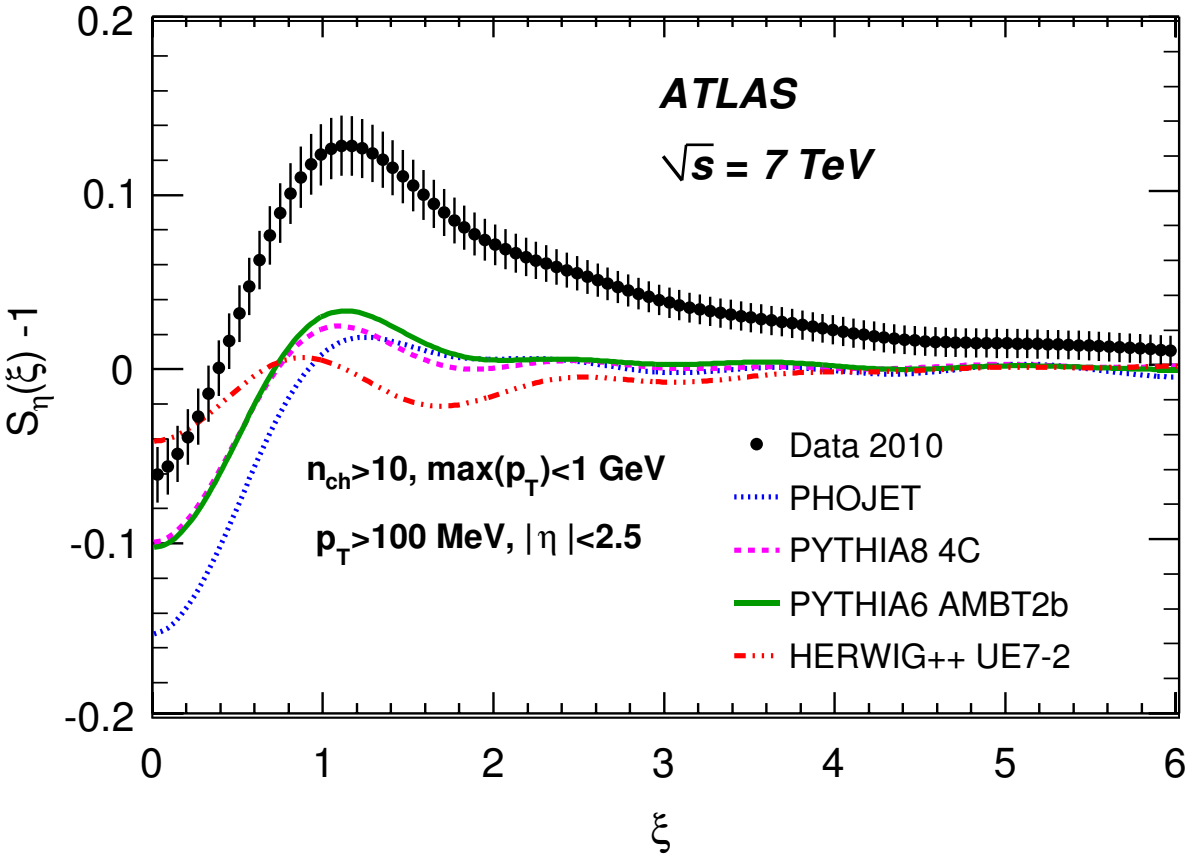
ξ is a scale parameter

Inclusive selection



Inclusive charged particle selection: $0.1 < p_{\mathrm{T}} < 10$ GeV

Low-p_{T} enhanced



$0.1 < p_{\mathrm{T}} < 1$ GeV — sensitive to hadronisation effects

Corresponding overshoot by MC in the low-p_{T} depleted sample, see backup

Event shape variables

Take the full momentum tensor of an event:

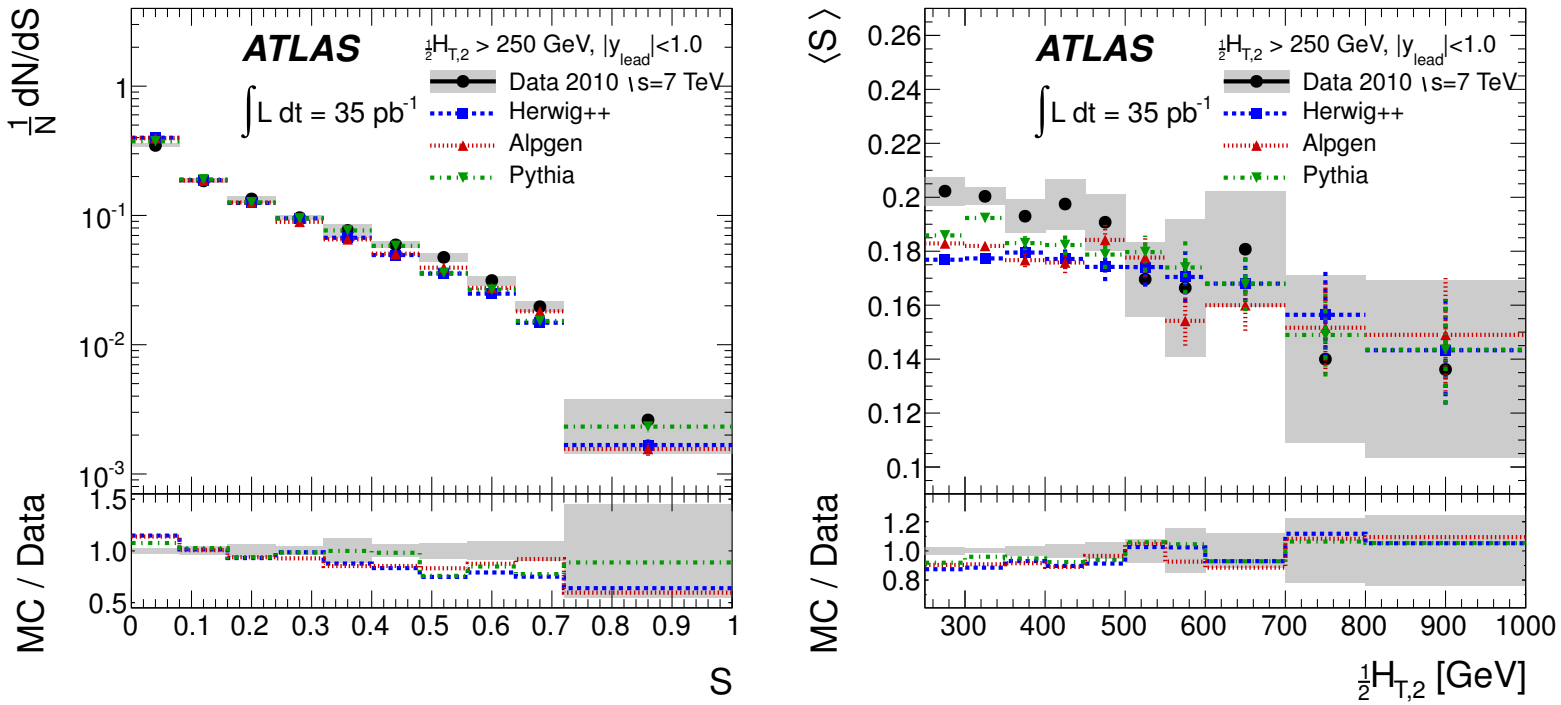
$$M_{xyz} = \sum_{\text{jets}} \begin{pmatrix} p_x^2 & p_x p_y & p_x p_z \\ p_y p_x & p_y^2 & p_y p_z \\ p_z p_x & p_z p_y & p_z^2 \end{pmatrix}$$

Find the ordered, normalised eigenvalues:
$\lambda_1 > \lambda_2 > \lambda_3, \qquad \sum_i \lambda_i = 1$

Define event shape variables:

- Sphericity: $S = \frac{3}{2}(\lambda_2 + \lambda_3)$
- Transverse sphericity: $S_\perp = \frac{2\lambda_2}{\lambda_1 + \lambda_2}$
- Aplanarity $A = \frac{3}{2}\lambda_3$

Sphericity

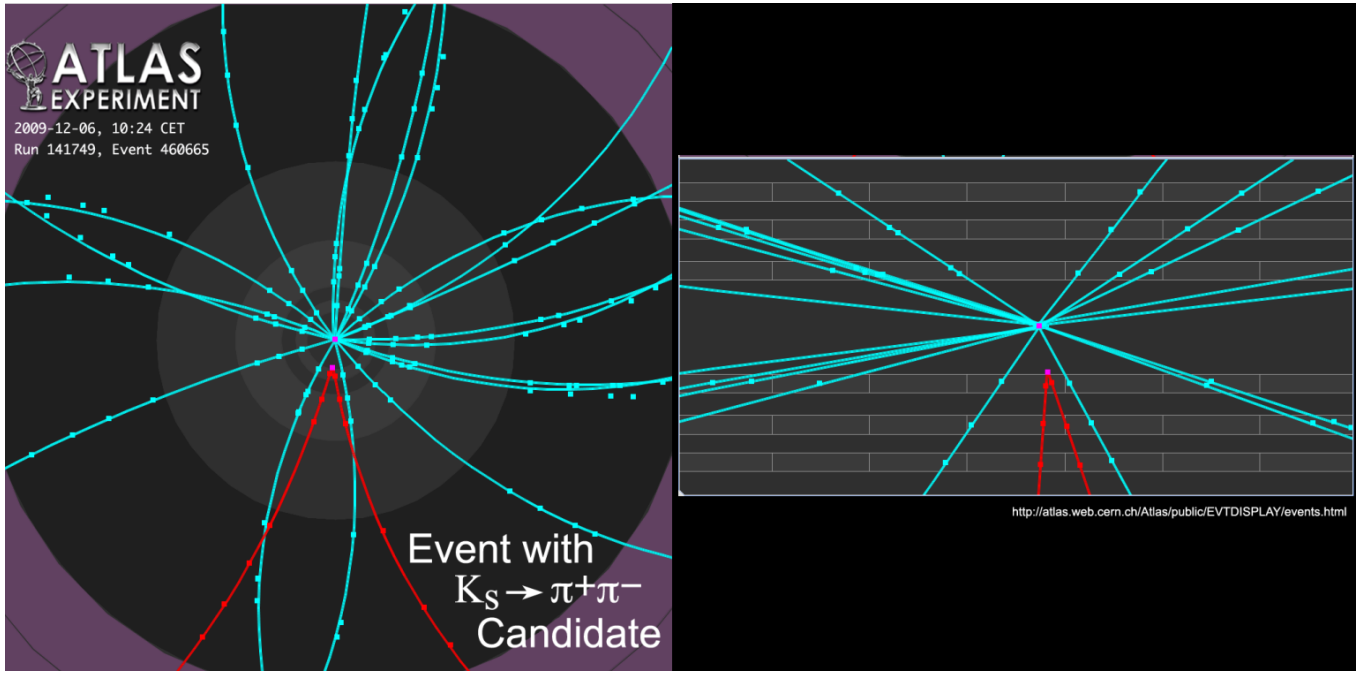


The sphericity spectrum and profile vs. the mean of the leading and subleading jet p_{T}

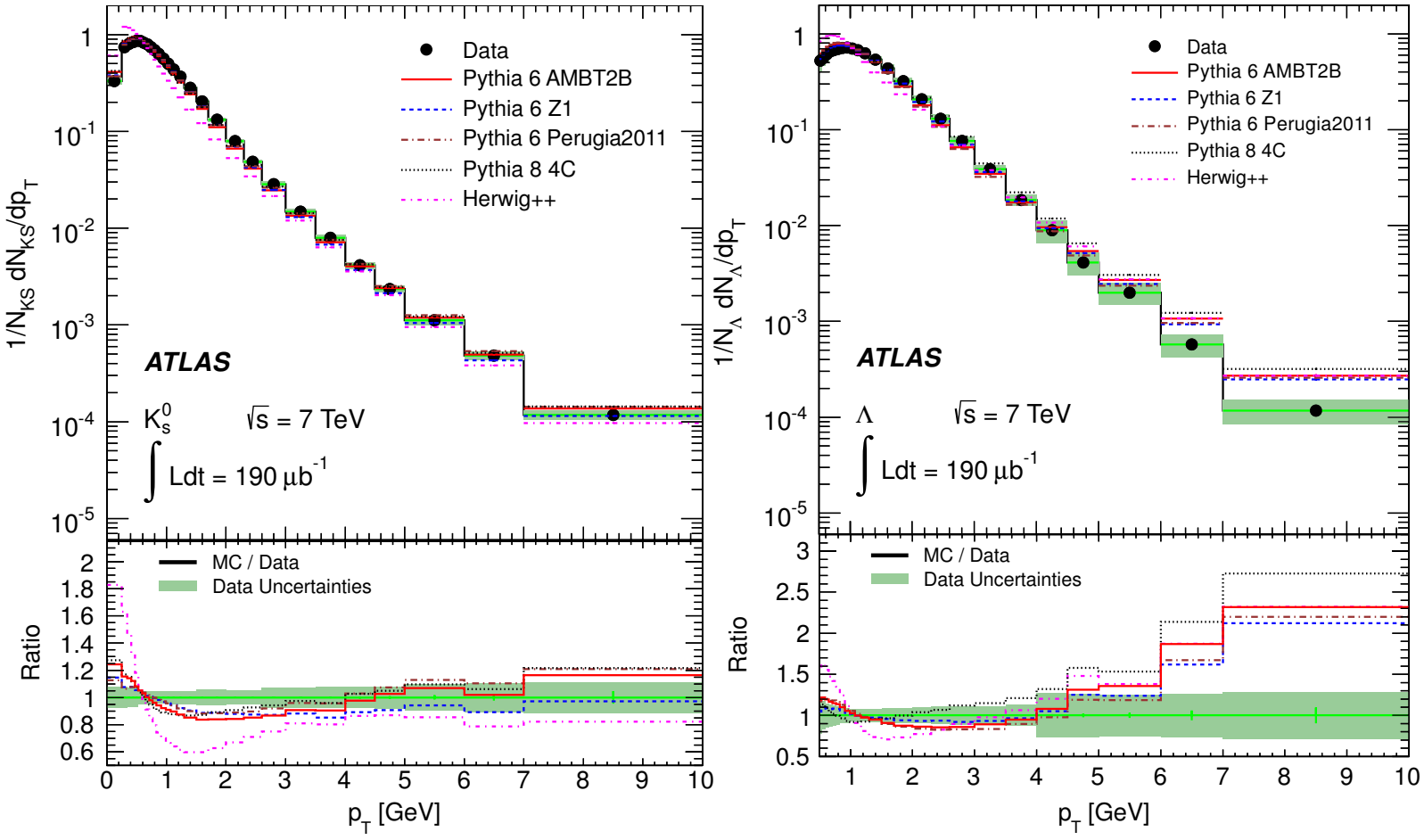
Similar trends for transverse sphericity and aplanarity, see backup

Identified strange hadrons

Identified using two oppositely-charged tracks forming a secondary vertex displaced 4–450mm (17–450mm for Λ)

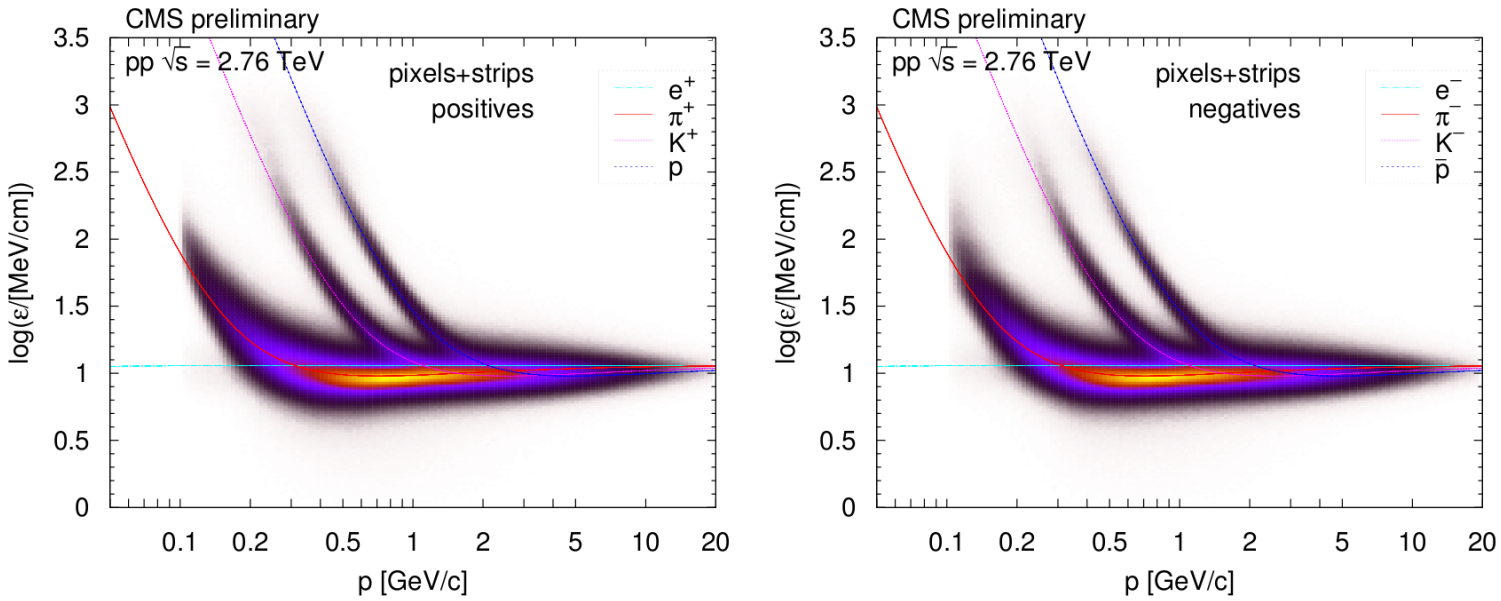


p_T spectra



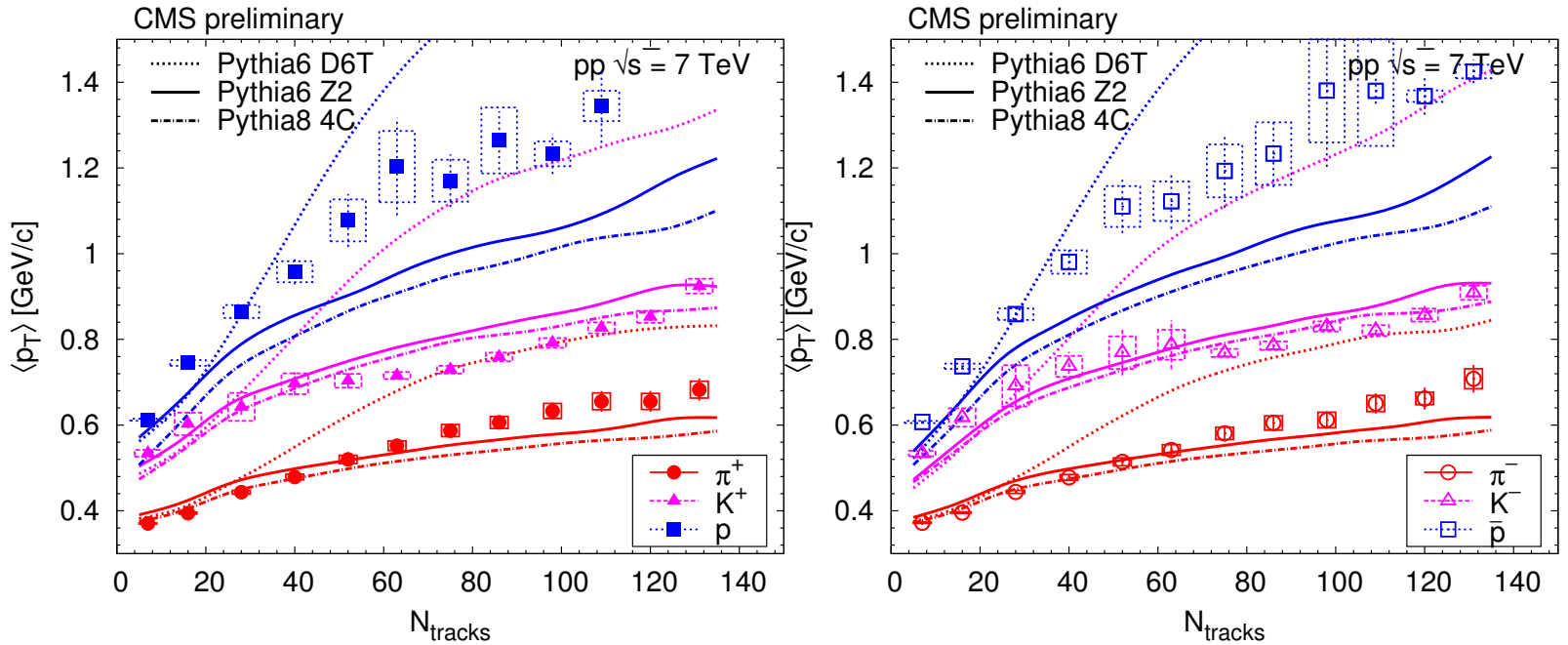
p_T spectra for K^0_s (left) and Λ (right)

Identified charged hadrons



Particles identified by tracker energy loss
Positive and negative particles on the left and right respectively

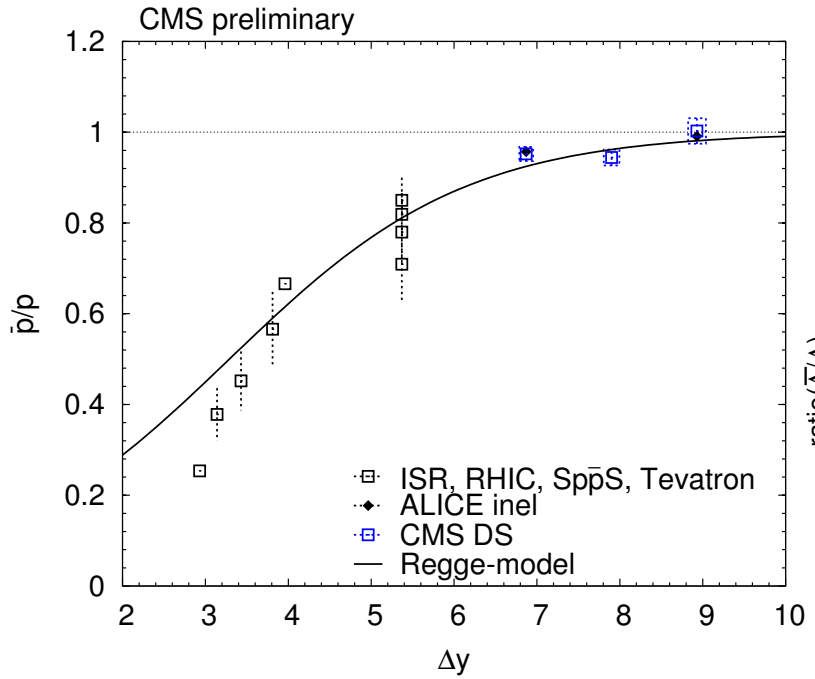
Kinematic distributions

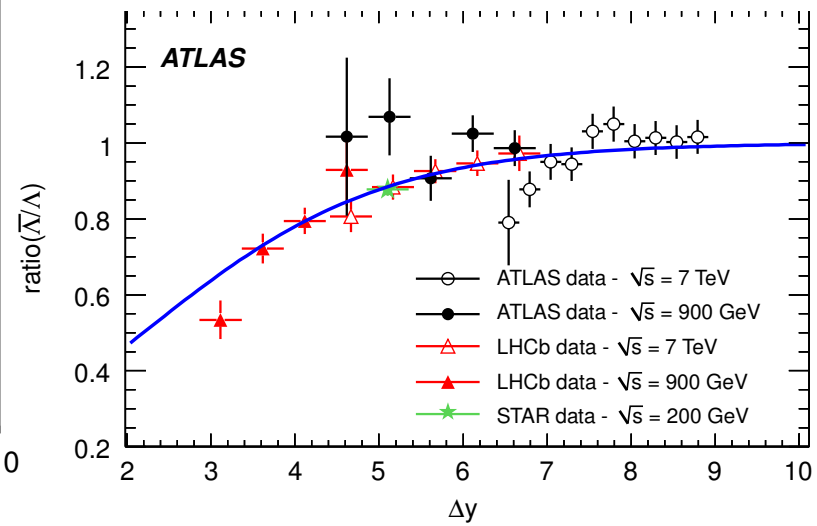


Profiles of the mean p_T of identified particles vs. the total charged particle multiplicity of each event

Positive and negative particles on the left and right respectively

Anti-particle : particle ratios





Ratios of detected (anti)particles, as a function of the rapidity difference $\Delta y = y_{beam} - y_{baryon}$

($y_{beam} \simeq 8.9$ and 6.9 at 7 TeV and 900 GeV, respectively)

Summary

Latest results show plenty of new features:

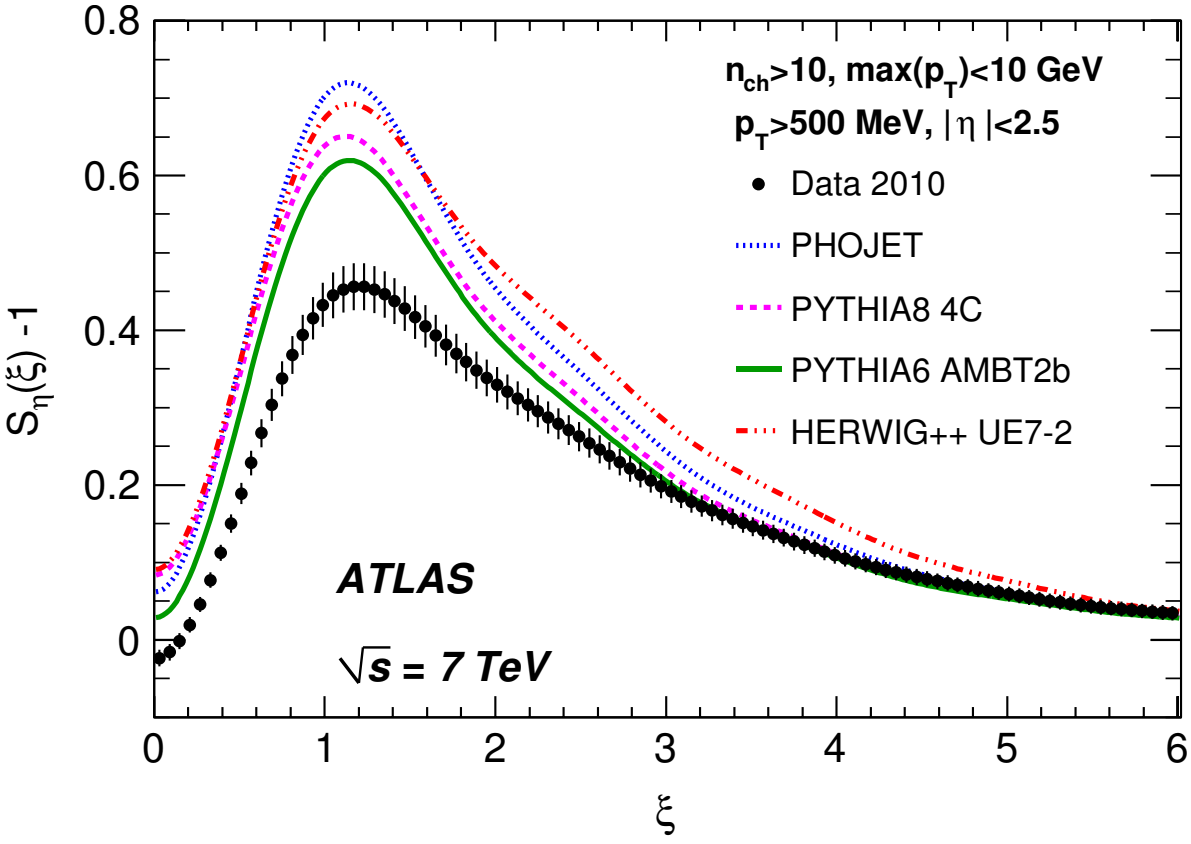
- ATLAS forward-backward $\sum p_{\mathrm{T}}$ correlation better modelled than multiplicity
- Azimuthal correlation less well modelled at large $|\eta|$
- Azimuthal ordering only modelled well in the inclusive sample
- Event shape values higher than expected at low $H_{\mathrm{T},2}$
- p_{T} spectrum of Λ-baryons in ATLAS not modelled as well as for K^0_{S}
- Proton kinematics in CMS not modelled as well as π and K

For Further Reading I

- ATLAS forward-backward and azimuthal correlations
  http://inspirehep.net/record/1093734
- ATLAS azimuthal ordering of charged hadrons
  http://inspirehep.net/record/1091481
- ATLAS event shapes at large momentum transfer
  http://inspirehep.net/record/1117887
- ATLAS K short and Lambda production
  http://inspirehep.net/record/944826
- CMS spectra of identified charged hadrons
  http://cdsweb.cern.ch/record/1434724

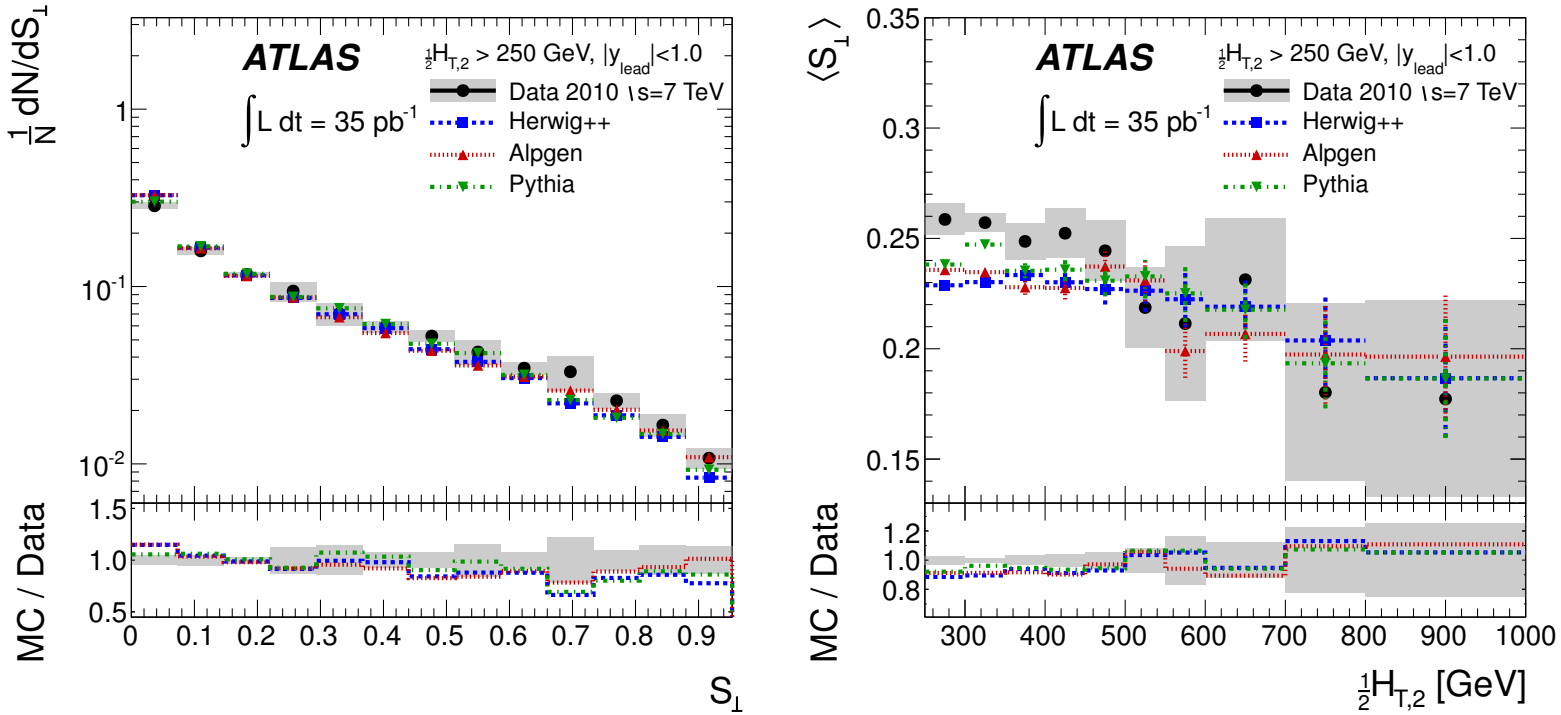
Backup

Low-p_{T} depleted



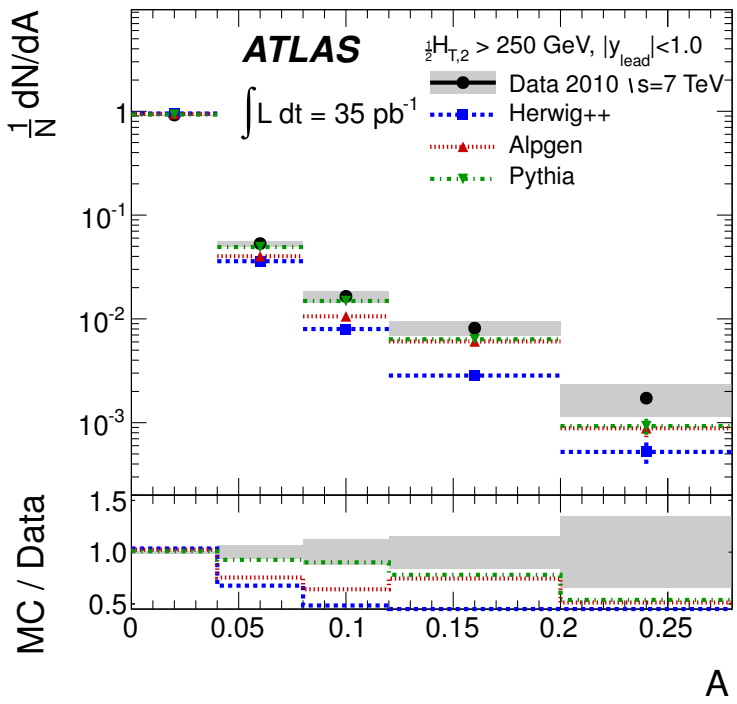
Low-p_{T} depleted sample (smaller contribution from diffractive events): $0.5 < p_{\mathrm{T}} < 10$ GeV

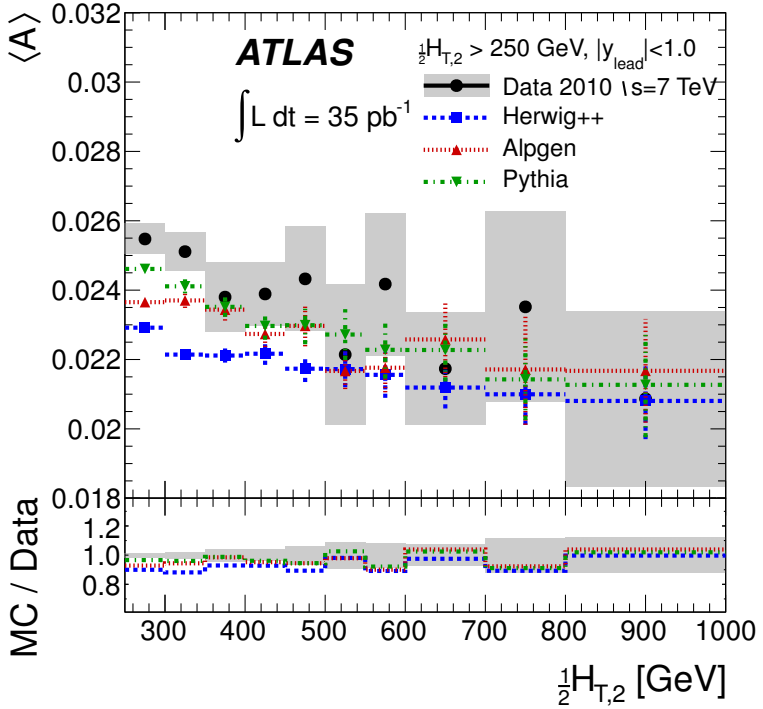
Transverse sphericity



The transverse sphericity spectrum and profile vs. the mean of the leading and subleading jet p_{T}

Aplanarity





The aplanarity spectrum and profile vs. the mean of the leading and subleading jet p_{T}